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## **Monitoring the hygrothermal and ventilation performance of retrofitted clay brick solid wall houses with internal insulation: Two UK case studies**

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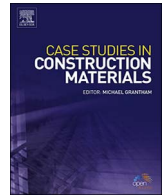
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## Case study

## Monitoring the hygrothermal and ventilation performance of retrofitted clay brick solid wall houses with internal insulation: Two UK case studies

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## ABSTRACT

This work assesses the hygrothermal and ventilation performance of two 'hard-to-treat' historic, clay brick, solid wall houses that are internally insulated. Retrofit A is a two bedroom bungalow with the addition of internal plasterboard and air cavity and Retrofit B is a 5 bedroom house with sheep wool, phenolic and plasterboard insulation. To evaluate the long term performance of the retrofit measures, the testing is carried out 7 and 8 years respectively after completion. The first part of the work investigates whole building hygrothermal performance, ventilation and internal conditions. It was found that both retrofits are operating below specification in regards to their ventilation performance. An *in-situ* performance based specification for mechanical ventilation via CO<sub>2</sub> monitoring is proposed. The second part focuses on the hygrothermal behaviour of the clay brick wall assembly. Both presented high relative humidity within critical layers of the wall make up. In Retrofit A the wall thermal transmittance was found to be much higher than designed due to inappropriate construction detailing while Retrofit B showed excellent thermal performance and minimal effects of thermal bridging.

## 1. Introduction

The UK government has committed to legally binding targets to lower its total CO<sub>2</sub> equivalent emissions by 80% of 1990 levels by the year 2050 [1]. In 1970 the UK domestic housing stock contributed 24–27% of total UK CO<sub>2</sub> emissions but this has risen to 28–36% [2,3]. Exacerbating this, existing housing stock in the UK is also aged and underperforming with the most recent review of UK standard assessment procedure (SAP) ratings it was found the housing stock averaged 52/100, which corresponds to an energy efficiency rating 'E' [4]. It is estimated that approximately 60% of current UK housing stock will be standing in 2050 [5,6] and that the average SAP rating of buildings will have to be at least a 'B' to achieve CO<sub>2</sub> levels proposed in the UK Climate Change Act. Due to these facts widespread retrofitting is unavoidable and is recognised by both academia and industry [7,8].

To contextualise this, there are 9.2 m 'hard to treat' homes in the UK, being defined as having solid walls, no space for roof insulation, have no gas network connection or are high rise [9]. Of this number, 6.5 million are solid wall [9] and have been widely recognised as being particularly hard to treat with retrofit actions due to both technical issues and cost [9,10]. Focusing particularly on solid walls, improvements in the thermal performance can be achieved in two ways: externally retrofit insulation or internally retrofit insulation. External insulation can be used to achieve thermal transmittances similar to or better than modern cavity construction, which is common in UK new build houses [11], is faster to fit than internal insulation and may improve the appearance of a

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deteriorated structure [12]. This being said, in some cases external insulation can be unsuitable. In the case of historic buildings conservation laws can ban its use and its widespread application may diminish the architectural heritage of a locality. Due to this internal wall insulation cannot be avoided but concerns exist over moisture build up in the building fabric, interstitial condensation [13], thermal bridging losses [12] and durability issues [14].

The hygrothermal performance of an internally insulated solid wall house is particularly important due to the more porous nature of historic building materials compared to their modern counterparts [15] with this being highlighted as a particular issue in climates like the UK [16]. Previous case studies have shown conflicting results: there are clearly concerns with moisture build up within the insulation layers [15–17] but others have found the reduced drying effect of internal insulation to be negligible [18] and in one study it was shown no condensation formed during a 4 year monitoring period [19]. In another study, [20] four different internal insulation systems were installed on the internal face a 430–510 mm brick wall with materials then monitored for 9 months after installation. The measured and modelled results showed that the hygrothermal risk was directly related to the moisture content within the existing brick at the time of installation, therefore the time of installation is a critical factor. The interaction between the hygrothermal performance of the wall assembly and the whole building hygrothermal and ventilation performance is important in retrofitted structures, with many studies modelling these phenomena [21], with [22] focusing specifically on solid wall buildings.

From available literature only limited information is available on the hygrothermal performance of case study ‘hard to treat’ houses [22] and [23] also notes the gap between hygrothermal design practise and what is seen *in-situ* in.

To gain a holistic view of the hygrothermal performance of two ‘hard-to-treat’ internally insulated solid wall houses, this work is split into two sections. Firstly the whole building hygrothermal and ventilation performance is assessed and secondly the hygrothermal performance of the internally insulated wall is investigated. The review on Retrofit A and B is taking place 7 and 8 years respectively after completion, meaning a long term review of the home is being considered therefore problems not immediately identifiable at completion are considered, such as moisture build up and condensation issues.

## 2. The case studies: two retrofitted solid wall houses

The first case study house (Retrofit A) is a two bedroom solid wall red brick bungalow built in 1885, and is located 10 miles outside Belfast, Northern Ireland. The house is maintained by a Social Housing Association hereafter referred to as ‘landlord’ and is rented out to tenants hereafter referred to as ‘occupier’. The structural layout and insulation levels of the house remained largely unchanged until 2005 when measures to improve the energy efficiency of the house were introduced. These upgrades included the addition of internal insulation, upgrading of loft insulation and the addition of a mechanical ventilation and heat recovery (MVHR) system. The layout of the bungalow can be seen in Fig. 1 and an overview of the design specification before and after retrofit in Table 1. It is important to note that the house is a Grade II Listed Building (a UK protected historical building) therefore limiting the external work that can be implemented, including the replacement of the single glazed sash windows. This type of building poses a particular problem to designers and the landlord. A balanced approach is needed to improve the performance of the house with consideration for architectural conservation, CO<sub>2</sub> emissions and occupant running costs.

The second property investigated (Retrofit B), maintained by the same landlord, is a four bedroom solid wall red brick house built in 1878 and located in central Belfast, Northern Ireland. The building was in a state of disrepair before renovation work was completed in 2007. Walls were internally insulated, double glazing installed, space heating provided by an air source heat pump and ventilation via a MVHR system. Layout and design specifications can be seen in Fig. 1 and Table 1 respectively.

These two buildings represent the first houses that the landlord retrofitted with energy saving solutions, and were selected for investigation to gain an understanding of the long term effect of the alterations on the hygrothermal performance of the building. Testing was carried out in the same month in spring at both properties. Average temperatures in the region for this month were 6.5 °C (1.1 °C below the 1981–2010 average) with 77.3 mm of rainfall (long term average 75.0 mm) with the sunshine levels being 113% of

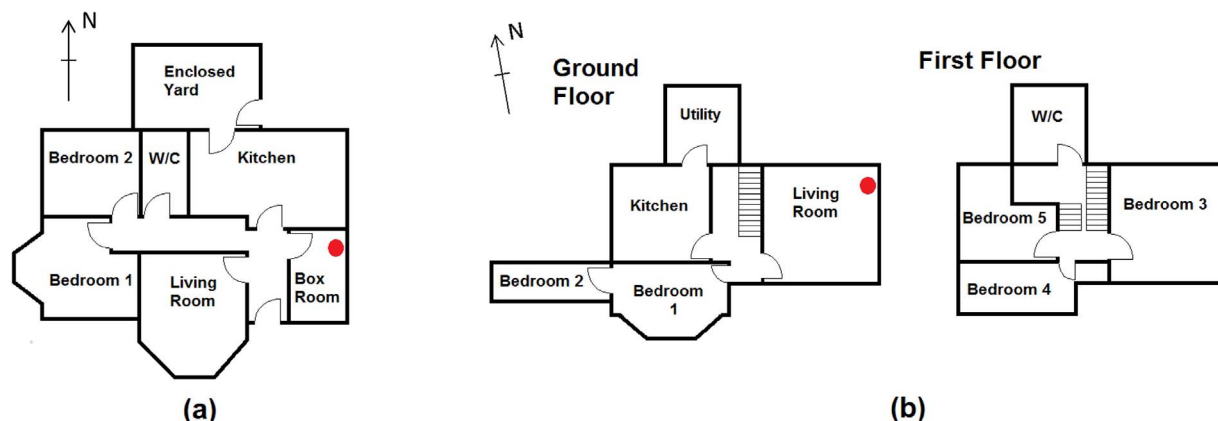


Fig. 1. (a) Floor plan of Retrofit A (b) Floor plan of Retrofit B. Red dot denote wall monitoring locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 1**

Retrofit Summary: Blower Door Test Results and Design Thermal Transmittance.

	Unit	Retrofit A		Retrofit B	
		Pre Retrofit	Post Retrofit	Pre Retrofit	Post Retrofit
Air-changes per hour at 50 Pa	ACH	N/A	8.9	N/A	2.0
Air Permeability at 50 Pa	m <sup>3</sup> /h/m <sup>2</sup>	N/A	5.6	N/A	2.0
Ground floor	W/m <sup>2</sup> /K	1.5	1.5	1.5	0.21
Walls	W/m <sup>2</sup> /K	2.9	1.05	2.9	0.24
Roof	W/m <sup>2</sup> /K	1.7	0.19	1.7	0.19
Windows	W/m <sup>2</sup> /K	4.8	4.8	4.8	1.8

the long term average. Results from this work will feed into a larger monitoring and retrofit program currently being developed by the landlord.

### 3. Methodology

This work is split into two sections: the first looks at the whole building hygrothermal performance and ventilation; the second focuses on the hygrothermal interactions within the interior insulation systems of the solid wall. This approach allows a detailed holistic overview of the long term hygrothermal performance of the retrofits to be formed while causing minimal disruption to the tenants of the property. The holistic approach will also determine if further monitoring is required on focused areas of concern.

#### 3.1. Part 1: whole building hygrothermal and ventilation investigations

For Part 1 the whole building hygrothermal and ventilation performance is analysed to investigate whether there was a need for mechanical ventilation and to compare internal conditions to recommended guidelines. The passive ventilation rate and air permeability were found experimentally and internal temperature, humidity and CO<sub>2</sub> were monitored *in-situ*. Each building was fitted with a mechanical ventilation and heat recovery system (MVHR) but these were not in use during any of the testing.

##### 3.1.1. Passive ventilation – decay tracer gas test

Tracer gas tests were carried out on both properties to determine the natural building air leakage rate under normal operating conditions known as the passive ventilation or passive infiltration rate of the building. The test was carried out in accordance to ISO 12569:2000 [24] using Wohler CDL210 data loggers to trace the natural decay with time of the trace gas, in this case CO<sub>2</sub>. To determine the natural infiltration rate a volume of tracer gas was injected into the area under investigation and the decay monitored at constant intervals. Three locations were studied within the building and an outside location was used as an external benchmark of background concentration. The CO<sub>2</sub> readings from the three internal loggers were averaged and the decay used to determine the whole house passive ventilation rate.

##### 3.1.2. Air permeability – blower door test

As lower air permeabilities have been shown to lead to lower energy demands [25], blower door tests were carried out on both properties to determine the air permeability. The test was carried out in accordance with the UK building regulation standard BS EN 13829:2001 [26] and the equipment was calibrated as outlined in the best practise guide ATTMA TS1 [27]. The blower door system was inserted into a doorway of the building and the building pressurised to a differential of approximately 70 Pa. Building leakage rate, Q (m<sup>3</sup>/h) was logged from the calibrated fan speed and was taken automatically every 5 Pa from 30 Pa to 70 Pa pressure differential. Readings were plotted on a graph and the air leakage at exactly 50 Pa interpolated from the line of best fit. The air permeability (Q50) was calculated from this interpolated value using equation 1. The air changes per hour at 50 Pa can also be determined using this value in conjunction with Eq. (2).

$$Q_{50} = \frac{Q}{S} \quad (1)$$

$$n_{50} = \frac{Q}{V} \quad (2)$$

Where, Q is the air leakage at 50 Pa pressure differential (m<sup>3</sup>/h), S is the internal surface area of the building measured along the air barrier (m<sup>2</sup>) and V is the volume of the building within the air barrier (m<sup>3</sup>).

The Energy Saving Trust [28] and BRE [29] have issued guidance on the specification of MVHR systems using the air permeability test results. The BRE recommends that for optimum performance of a MVHR system the air permeability of the house calculated at 50 Pa (Q50) should ideally be less than 3 m<sup>3</sup>/h/m<sup>2</sup>, however, a MVHR system is deemed satisfactory on houses with air permeability up to 5 m<sup>3</sup>/h/m<sup>2</sup>. The same blower door test can be used to determine the air changes per hour at 50 Pa (n50) using equation 2. This n50 metric is widely used by the Passive House Institute for building design and specification of MVHR systems. Using this metric [25] found that MVHR systems only become economically viable for energy reduction when the building has an n50 value less than

### 3ACH.

#### 3.1.3. CO<sub>2</sub> Concentration

Concentration of CO<sub>2</sub> is often used as a proxy for indoor air quality [30] due to its relative ease of measurement but it is scientifically limited due to its lack of direct correlation to indoor air quality parameters such as volatile organic compounds or formaldehyde [31]. Even with this limitation CO<sub>2</sub> levels are a valuable indicator for adequate ventilation rates with concentrations being linked to airborne communicable infection via inhalation of exhaled air using the Wells-Ridley equation [32]. Other recent studies have shown that CO<sub>2</sub> concentrations in excess of 1000 ppm have adverse effects on the decision making performance of individuals [33] and [34] recommends that maximum levels of CO<sub>2</sub> should be 1350 ppm.

CO<sub>2</sub> concentration was logged in 5 min intervals over 450 h in the main bedroom of each building due to the high number of occupancy hours overnight. The bedroom was selected to simulate the worst case scenario as most people sleep with the door closed for privacy and reduced fire risk resulting in low ventilation compared to other rooms.

#### 3.1.4. Internal temperature and relative humidity

The floor plans of the two properties are shown in Fig. 1. Internal temperature and humidity was monitored in the three main rooms of each property, the bedroom, living room and bathroom (denoted as W/C in Fig. 1). The living room and bathroom were monitored for a period of 960 h (40 days). The bedroom was monitored for a shorter time period of 480 h (20 days) due to data logger capacity. Temperature and relative humidity measurements were taken in the centre of the rooms using data loggers accurate to  $\pm 0.5$  °C and  $\pm 3\%$  relative humidity.

#### 3.1.5. Ventilation performance

Observations were made on the design and installation process and of the MVHR systems in each retrofit. During the investigations the MVHR system was not in operation in either property.

### 3.2. Part 2: hygrothermal investigation of solid wall

The hygrothermal performance of the wall is assessed via *in-situ* heat flux measurement, humidity analysis of the wall make up and thermal bridging analysis via quantitative infrared imaging.

#### 3.2.1. In-situ thermal transmittance (U-Value)

An *in-situ* thermal transmittance measurement was carried out in each of the properties. Two Hukseflux HFP01 Heat Flux Sensors were used in Retrofit A and B for monitoring periods of 350 and 250 h respectively to assess the heat flux through the wall. Heat flux sensor positioning within the houses has been denoted in Fig. 1 with a red dot. Both houses had the sensors placed on the easterly orientation of the wall, 1.5 m from the floor. Data from the initial 48 h period after sensor installation was ignored to allow temperatures across the heat flux plate to stabilize. Measurements were recorded on a 16bit data logger with an accuracy of 1  $\mu$ V suitable for the nominal sensor accuracy of 50  $\mu$ V/W.m<sup>2</sup>. Sensors were mounted to the wall with sticking tape using a heat sink paste to ensure good thermal contact. A small film of plastic was placed between the heat sink paste and the wall to protect the internal finish and was found to cause negligible sensor error. Calibration of the sensor in conjunction with this mounting technique was carried out in the laboratory prior to site installation and it confirms the manufacture accuracy of  $\pm 5\%$ . The average values obtained from the two sensors in each property was calculated to improve spatial accuracy.

#### 3.2.2. Wall temperature and humidity profile

The wall humidity and temperature profile was monitored for a period of one week to assess the risk of moisture build up and condensation risk within the building fabric as this could cause damage to the structure, mainly timber joists and the insulation. Honeywell HIH4000 relative humidity sensors and T-type thermocouples were connected to a 16 bit data logger to provide high accuracy readings. Sensors were calibrated in the laboratory to confirm manufacture stated accuracies of  $\pm 3\%$  and 0.5 °C respectively. Internal and external temperature and humidity were measured as well as embedded locations through the wall as shown in Fig. 1. Embedded measurements were taken by drilling holes into the wall from the interior face and inserting a plastic tube into the desired depth. The drilled hole was stepped from 12 mm diameter to 10 mm diameter at the sensing location and the tubing end pushed tightly into this to ensure measurement at the exact location needed. The end of the tubing was fitted with a breathable membrane and a rubber seal in the tubing ensured that air only entered through the membrane as shown in Fig. 2. Sensors were installed at a height of 1.3 m from the internal floor to insure that results were not affected by rising damp or thermal bridging effects. Thermal images and internal surface moisture readings confirmed that the areas were free from abnormal defects and no cracking was observed internally or externally. The locations investigated were within 300 mm of the location of the heat flux measurements on the easterly elevation. Measurements were taken in the building 7 years after installation of retrofit measures for Retrofit A and 8 years after installation of retrofit measures in Retrofit B. Data was gathered for a period of 7 days at 5 min intervals to find an average condition for the property and to allow adequate stabilisation of the sensors.

#### 3.2.3. Quantitative detection of thermal irregularities by infrared imaging

Recent publications in the use of infrared (IR) thermography have highlighted its many advantages in regards to assessment and quality control of energy efficient buildings. [35] provides a comprehensive review of IR applications in assessing quality of

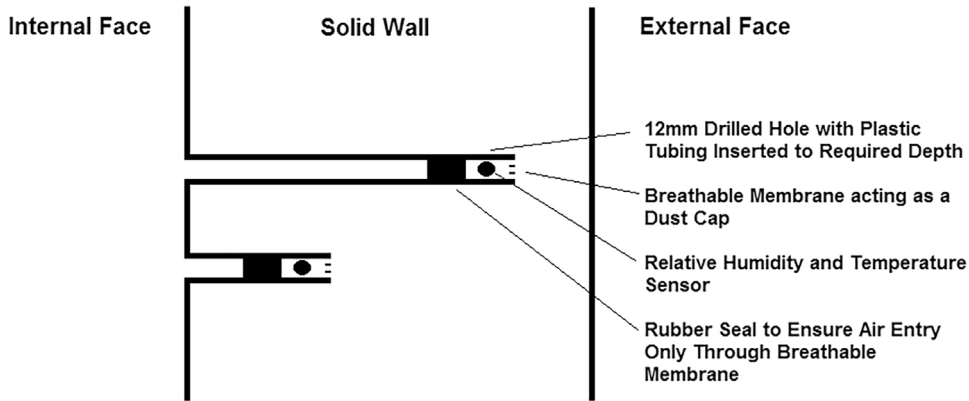


Fig. 2. Schematic of Wall Temperature and Humidity Sensor Installation.

workmanship in new build houses but little analysis of retrofitted houses is available. In the retrofit case qualitative analysis is more difficult due to the uncertainty regarding building construction materials; make up and in the case of historic materials inhomogeneous properties. Analysis of both case study buildings was carried out to gain an in depth understanding of the effect of thermal bridging on the building performance as thermal bridging is often highlighted as an issue with internal insulation systems. Thermal bridging is known to cause excess heat loss and also increase the risk of condensation forming on the cold internal surfaces.

An infrared thermography survey of both properties was carried out in accordance to BS EN 13187:1999 [36] with infrared images being taken during periods of low solar radiation, just before dawn, and digital images taken during daylight. Table 4 outlines the environmental and infrared conditions during this imaging work.

Using the methodology proposed by [37] the effect of this thermal bridge on the thermal transmittance at this location can be estimated with a confidence level of 95% when an *in-situ* thermal transmittance test is carried out on non-bridged location. Analysis of thermal bridging effects from the temperature field observed with the IR camera is possible *via* a reverse analysis of the linear thermal bridging equation presented in BSI EN ISO 10211, equation 3 [38].

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \quad (3)$$

Where  $\Psi$  is the linear thermal transmittance, W/(mK),  $L_{2D}$  is the thermal coupling coefficient obtained from a 2D calculation of the component separating the two environments being analysed,  $U_j$  is the thermal transmittance of the 1D component,  $j$ , separating the two environments and  $l_j$  is the length over which the  $U_j$  value applies (m). Quantitative analysis of thermal bridges using thermographic surveys and post processing is therefore possible. Based on the linear thermal bridging Eq. (3) an area of known thermal transmittance, either from *in-situ* testing or theoretical design, can be related to the heat loss through an area of thermal bridging *via* the use of an incidence factor,  $I$ , which relates the heat flux through a known area of thermal transmittance to the heat flux through a thermal bridge *via* Eq. (4). The heat flux of the thermal bridge can then be related to the incidence factor with Eq. (5).

$$I = \frac{\sum_{p=1}^N (T_{ext} - T_p)}{N(T_{ext} - T_{1D})} \quad (4)$$

$$U_{tb} = I \times U_{1D} \quad (5)$$

Where  $N$  is the number of pixels under analysis,  $p$  is the individual image pixel,  $T$  is temperature, ext is external, 1D is one dimensional,  $U$  is the thermal transmittance and tb is thermal bridge.

**Table 2**  
Test Conditions and Results of Tracer Gas Test.

	Unit	Retrofit A	Retrofit B
Average Internal Temperature	°C	14.0	22.0
Average External Temperature	°C	6.0	15.0
Average Wind Speed	m/s	3.0	2.8
Passive Ventilation Rate	ACH	0.2	0.56



#### 4. Part 1: whole building hygrothermal and ventilation performance

##### 4.1. Passive ventilation – decay tracer gas test

The determined passive ventilation within Retrofit A was 0.2 air changes per hour (ACH) while Retrofit B had a determined value of 0.56 ACH with the test conditions shown in Table 2. The recommended whole house ventilation rates as per BS5250:2002 [39] are 0.5 to 1.5 ACH for adequate condensation control. These tests indicate that Retrofit A has a below standard ventilation rate and Retrofit B is just within recommended levels.

Passive ventilation is affected by the pressure differential caused by the internal and external temperature gradients as well as the wind speed and direction [40]. As found by [41], these climate conditions can affect the test result, with the ventilation rate of a single zone brick building in a 4 month winter period varying between 0.06 and 0.37ACH. This means that during conditions which lead to lower pressure gradients than experienced at the time of testing, that natural ventilation rates could be significantly considerably lower than measured. This is significant as the passive ventilation test carried out on Retrofit B is just within recommended levels and this test result indicates there is no need for mechanical ventilation, but this may not be the case. Taking into consideration the findings of these test results, both Retrofit A and B may need to consider a MVHR system to supply the necessary ventilation to the building.

##### 4.2. Air permeability – blower door test

The air permeability (Q50) for Retrofit A is  $5.6 \text{ m}^3/\text{h}/\text{m}^2$  and Retrofit B is  $2.0 \text{ m}^3/\text{h}/\text{m}^2$  therefore both houses are within the UK building control standard of  $10 \text{ m}^3/\text{h}/\text{m}^2$  [34]. When looking at the Q50 and n50 results obtained from Retrofit A and Retrofit B (Table 1) in conjunction with the recommended values (Section 3.1.2 Air Permeability – Blower Door Test): Retrofit A does not need mechanical ventilation installed as both Q50 and n50 values fall outside the recommended tolerances; Whereas Retrofit B has a Q50 of  $2.0 \text{ m}^3/\text{h}/\text{m}^2$  and n50 of 2.0ACH suggesting that a MVHR system would be economical in operation within the building. It should be noted that internal health conditions could mean an MVHR is still required even if its operation is not deemed to be economical in energy saving terms- this is discussed further below.

##### 4.3. CO<sub>2</sub> Concentration

In Retrofit A the recorded CO<sub>2</sub> content does not exceed the upper limit of 1350 ppm for any time during the monitoring period,

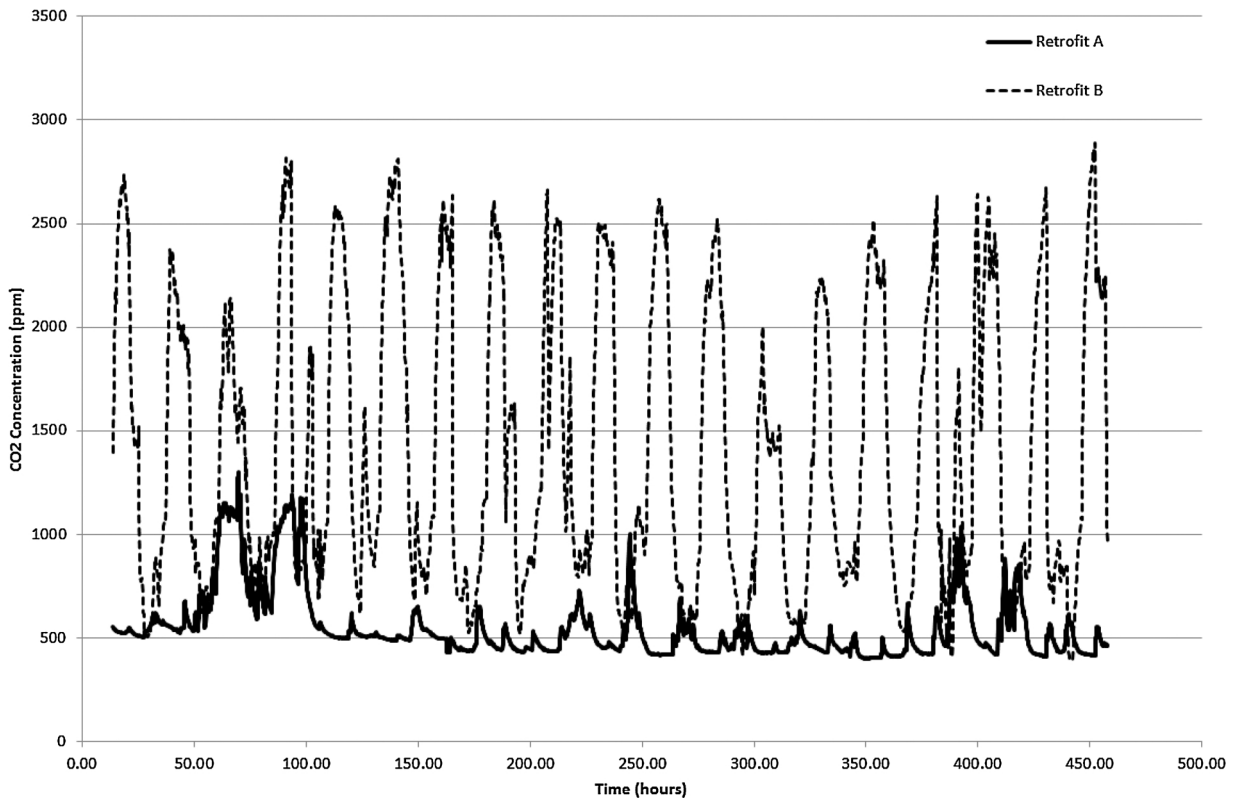


Fig. 3. CO<sub>2</sub> Concentrations in Bedrooms of Retrofit A and B.

**Table 3**  
Summary of Monitored Internal Conditions.

		Unit	Retrofit A	Retrofit B
Bathroom	Temperature (Mean)	°C	14.4	20.4
	Temperature (Std. Dev.)	°C	1.3	1.5
	Relative Humidity (Mean)	%RH	63.1	51.8
	Relative Humidity (Std. Dev.)	%RH	3.0	8.0
Bedroom	Temperature (Mean)	°C	14.8	21.4
	Temperature (Std. Dev.)	°C	1.8	0.6
	Relative Humidity (Mean)	%RH	54.8	49.1
	Relative Humidity (Std. Dev.)	%RH	4.7	6.4
Living Room	Temperature (Mean)	°C	17.1	22.6
	Temperature (Std. Dev.)	°C	2.0	1.2
	Relative Humidity (Mean)	%RH	54.2	42.9
	Relative Humidity (Std. Dev.)	%RH	4.4	4.9

shown in Fig. 3. Average CO<sub>2</sub> levels of 551 ppm and a peak of 1300 ppm were recorded. This indicates that ventilation rates within the bedroom are adequate for the current occupancy. This property is occupied 24 h a day by the tenant and this translated to an area of 90 m<sup>2</sup>/person.

Within the bedroom of Retrofit B a significant period of the monitoring time was above CIBSE maximum CO<sub>2</sub> values [34] with the average reading being 1414 ppm with a peak value of 2889 ppm, Fig. 3. The bedroom exceeded 1350 ppm for 202 h of the 450 h monitoring period, equating to 45% of the time. This shows that the ventilation rate of the room is insufficient to maintain healthy internal conditions during the night time period. The property is occupied by four persons 24 h a day with an occupancy area of 35 m<sup>2</sup>/person. Although the space per occupant within Retrofit B is significantly less than Retrofit A, and is likely contributing to the higher CO<sub>2</sub> values, the total house area of 140 m<sup>2</sup> still well above the minimum 97 m<sup>2</sup> set by the UK government. (GOV REF) When looking at this data in conjunction with the whole house tracer gas tests, although the passive ventilation results fall just within recommended values, the CO<sub>2</sub> monitoring has highlighted that there is not sufficient ventilation to ensure recommended conditions in the bedroom during night time hours.

#### 4.4. Internal temperature and relative humidity

The average temperatures within Retrofit A are significantly lower than the CIBSE [34] recommended internal temperatures of 19–24 °C for living areas and 17–19 °C for bedrooms with the average living room and bedroom temperatures being 17.1 °C and 14.8 °C respectively as shown in Table 3 and Fig. 4. This shows that even with existing retrofit measures the tenant is not able to maintain the house at a comfortable level, although this is influenced by both socio-economic and technical factors. Relative humidity measurements were found to be within the recommended guidance of 45–55% [34] with occasional peaks in the bathroom being quickly brought back to with acceptable limits by the extractor fan. This shows that the current ventilation strategy in regards to humidity dissipation within the building is adequate, although internal temperatures are low.

Both the average temperature and relative humidity within Retrofit B were found to be within recommended guidelines [34], Table 3 and Fig. 5. This indicates that the ventilation strategy is dissipating humidity within the building with temperatures also remaining within the current guidelines.

#### 4.5. Ventilation system performance

Both Retrofit A and Retrofit B had MVHR systems installed during the renovation of the properties but neither of the systems were in use at the time of assessment. During occupant interviews it was found that the owner of Retrofit A did not like the system turned on as they felt it caused drafts, particularly in the bedroom as an air inlet was located above the bed and was not effectively distributing the air in a diffusive manner. The occupier also commented that the air felt colder than that of the room. It was not possible to leave the system running to assess its *in-situ* performance due to occupancy requirements but it was noted that the system piping was not insulated in the loft area, meaning air provided would suffer additional heat loss after leaving the heat exchanger. In

**Table 4**  
Infrared Input Factors.

	Unit	Retrofit A	Retrofit B
Infrared Camera Resolution	–	320 × 240	320 × 240
External Air Temperature	°C	9.5	11.2
Reflected Temperature	°C	4.0	–40.0
Emissivity	–	0.81	0.81
Internal Temperature	°C	25.5	22.0



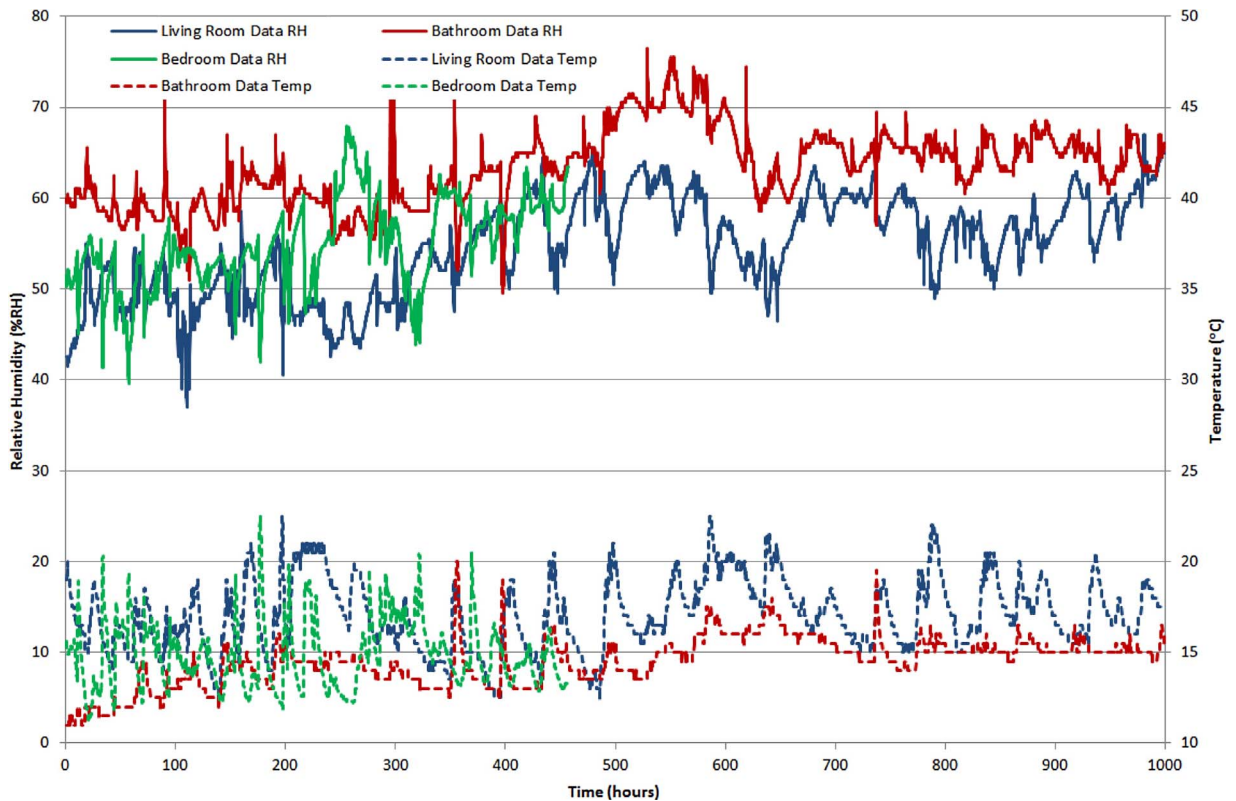


Fig. 4. Temperature and Humidity in Bedroom, Living Room and Bathroom of Retrofit A.

Retrofit B the occupiers also noted that the MVHR system made the room feel colder and they preferred not have the system running. Due to restricted access to the loft it was not possible to inspect this system visually and again it could not be turned on for testing due to occupancy requirements. These results highlight the need for both independent system testing on completion of installations and the importance of post occupancy evaluations as described by [42] and [43].

#### 4.6. Discussion on whole building hygrothermal performance

The internal whole building hygrothermal conditions were assessed by numerous tests, which in some cases produced conflicting results. Considering the results gathered for Retrofit A, the passive ventilation rate determined *via* the tracer gas decay method indicated that mechanical ventilation was needed as the rate was found to be 0.20ACH, below the recommended minimum of 0.5ACH. The results of the permeability testing *via* the blower door method found that Q50 and n50 values indicated any such MVHR system would not operate economically in regards to energy savings based on current recommendations. During *in-situ* testing of CO<sub>2</sub> concentrations during occupancy it was found that a MVHR system is not needed as CO<sub>2</sub> levels do not exceed recommended limits during actual use.

For Retrofit B the passive ventilation rate was found to be just within the minimum recommended levels of 0.5ACH at 0.56ACH, therefore a MVHR system would not be specified based on current guidelines. The Q50 and n50 values indicated that if a system was installed the permeability of the retrofit is sufficiently good that economical operation could occur. From the in use CO<sub>2</sub> monitoring it was found that an active MVHR system was needed to maintain ventilation rates, especially during the evening/night time hours of high occupancy.

The discrepancies in tracer gas test results compared to monitored conditions suggest that performance based specification of MVHR systems could be an economic alternative. The occupancy to floor area ratio within Retrofit A is 1:75 and in Retrofit B this ratio is 1:20 so therefore this increase in building capacity needs to be reflected in the ventilation rates designed for the building and is not done so by only using tracer gas testing. The passive interactions of ventilation are largely affected by building air tightness, temperature gradients, pressure differences as well as occupancy which results in a complex system to design when the final air-tightness of a building is impossible to predict accurately. Decisions on the inclusion of MVHR systems can be made from *in-situ* performance testing of CO<sub>2</sub> levels within the building after occupancy. Importantly *in-situ* performance testing includes the effect of all of the previously mentioned parameters during actual operation. With performance based specification MVHR systems would only need to be added to buildings which have been shown the need for them *via* CO<sub>2</sub> monitoring. During the design stage of a retrofit it should be considered that a MVHR system may need added at a later date if CO<sub>2</sub> levels, influenced by occupancy routines, show it

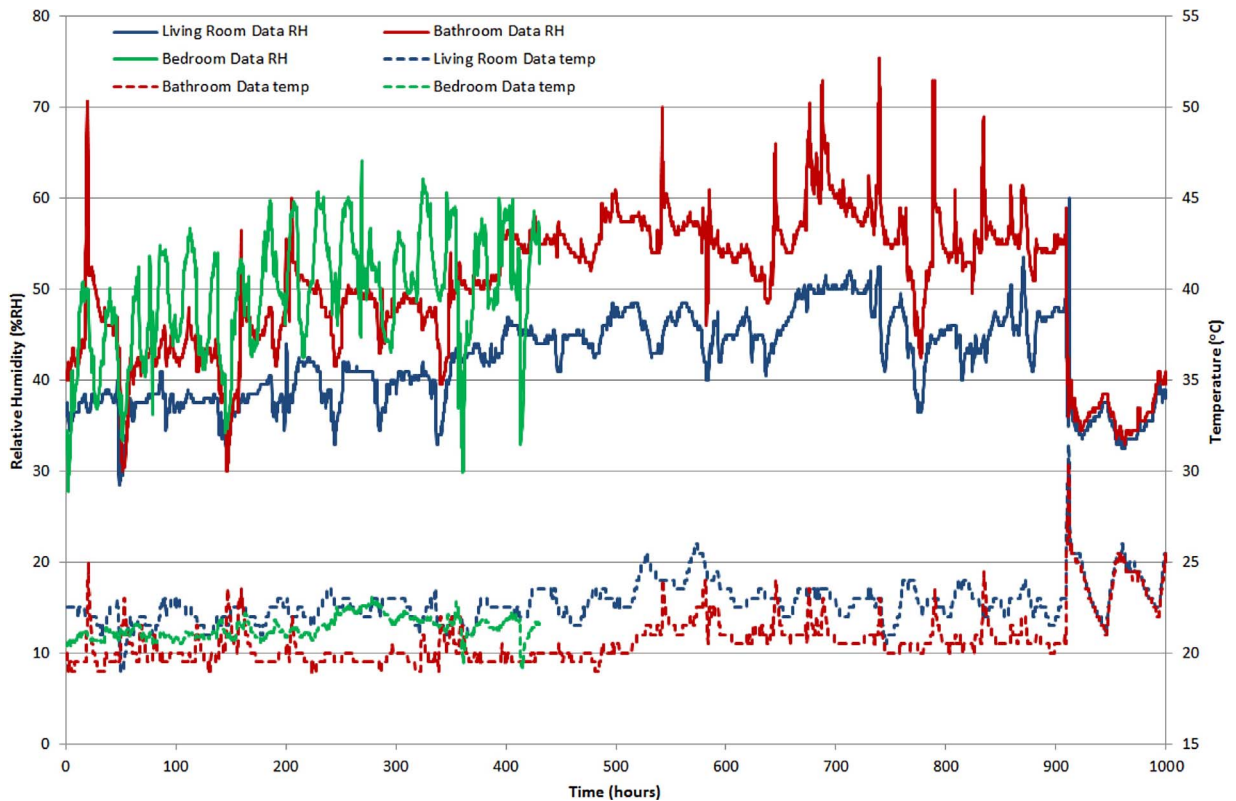


Fig. 5. Temperature and Humidity in Bedroom, Living Room and Bathroom of Retrofit B.

requires this. Some elements of ducting may need to be added during the initial retrofit action if they would be hard to fit at a later date. As the cost of ducting is small compared to the central fan and control system this should be given due consideration on a case by case basis. Performance based specification of Retrofit A would have shown that no system was needed within the building and a saving of £3500 could have been made on the retrofit costs.

In both Retrofit A and Retrofit B a MVHR system had been installed but was not working effectively so was not assessed during this testing regime. A robust commissioning and assessment protocol is vital to ensure their initial and continued efficient operation.

## 5. Part 2: hygrothermal performance of building fabric

### 5.1. In-situ thermal transmittance (U-Value)

The wall construction of Retrofit A consists of 225 mm historic red brick, a 30 mm cavity and 12.5 mm plasterboard which is secured to the wall with a light-weight metal framing system, Fig. 6(a). The thermal transmittance for the wall was found to be  $1.23 \text{ W/m}^2\text{K}$ . This value is higher than the design value of  $1.05 \text{ W/m}^2\text{K}$  and the data gathered was found to have a number of large variations in heat flux as shown in Fig. 7. There are two potential reasons for this variation, the first being the effect of rain on the porous external brick causing increased heat loss due to evaporating moisture and the second is due to air changes occurring in the cavity behind the plasterboard. This cavity space is open to air changes from an area of loft space which is not insulated as the mineral wool is not laid to the edge of the brickwork. There is not enough space for the required depth of mineral wool at this critical location due to the rafter meeting the wall plate as detailed in Fig. 6(a). The rate of air changes per hour in this cavity is dependent on the natural ventilation of the roof space and therefore the wind speed and wind direction. At the time of installation of sensors it was found that the air in the cavity was moving at up to  $0.01 \text{ m/s}$ , measured with a hot wire anemometer at a distance of  $1.3 \text{ m}$  from the floor. Movement of air within a cavity wall is known to occur due to the natural temperature gradient between the inner and outer wall leaf and also the use of cavity wall ventilation bricks. Thermal transmittance calculations as per BS ISO 6946:2007 [44] assume that there is limited air movement within the cavity and it follows that the calibration of the heat flux sensors are also effect by excess air movement in this zone. The accuracy of the reading in this location will have been affected by this excess air movement and will not be within the 5% tolerance expected from the laboratory calibration. It is therefore important that cavity ventilation is considered in all scenarios when heat flux sensors are used.

The wall construction of Retrofit B is 225 mm historic red brick, 75 mm sheep wool insulation with timber battens securing 35 mm polyurethane insulation and 12.5 mm plasterboard as shown in Fig. 6(b). The average thermal transmittance measured by the

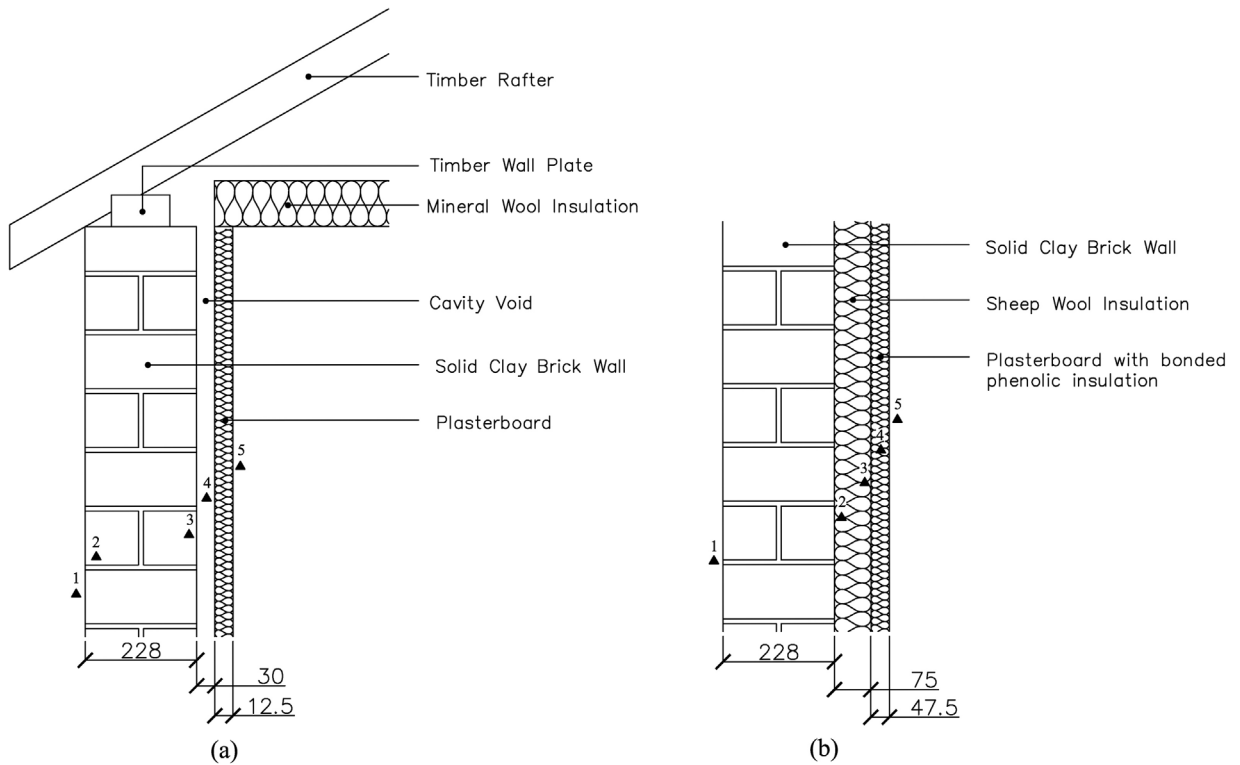


Fig. 6. (a) As Built Wall and Roof Assembly of Retrofit A (b) As Built Wall Assembly of Retrofit B.

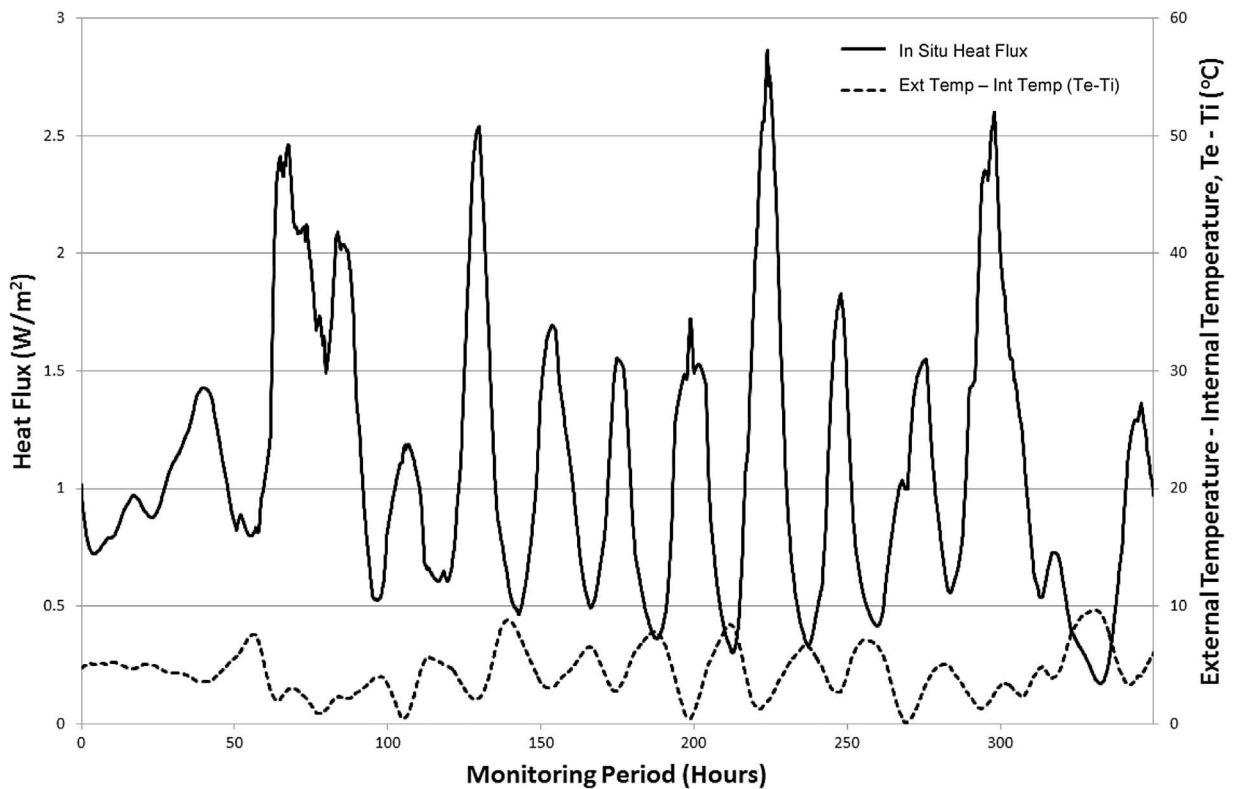


Fig. 7. Heat Flux through Wall Assembly of Retrofit A.

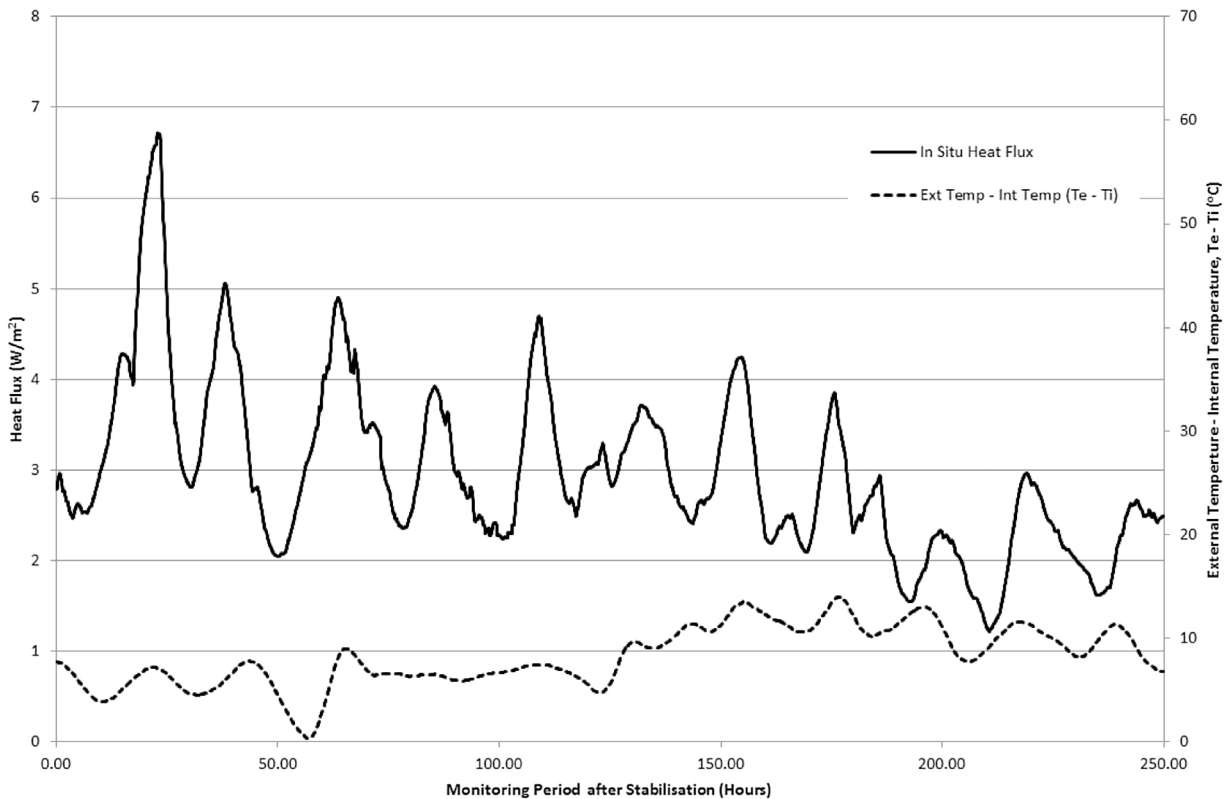


Fig. 8. Heat Flux from Wall Construction of Retrofit B.

two sensors over the monitoring period of 250 h was  $0.21 \text{ W/m}^2\text{K}$ , with the heat flux being shown in Fig. 8. This value shows that the wall performs better than the design value of  $0.24 \text{ W/m}^2\text{K}$ . The results of this test matched a previous *in-situ* thermal transmittance test carried out on completion of the retrofit project in 2007. This earlier test also calculated the thermal transmittance to be  $0.21 \text{ W/m}^2\text{K}$ . It can be concluded that there is no loss in thermal performance of the wall during the 8 years since completion.

### 5.2. Wall temperature and humidity profile

The sensor locations through the wall profile for Retrofit A are denoted by triangular markers and numbered 1–5 in Fig. 6a. The sensors are positioned so that the following locations are measured:

1. external environment
2. within the brick (30 mm from exterior face)
3. within the brick (190 mm from exterior face)
4. in the centre of the air cavity (240 mm from exterior face)
5. internal environment.

The temperature and humidity profile found is presented in Fig. 10. The sensor at the outer most brick location averaged a relative humidity of 87.9% (Std. Dev. 1.2%) and the inner brick sensor averaged 78.9% (Std. Dev. 1.1%), within the cavity this dropped slightly to 77.0% (Std. Dev. 1.4%). Within the air cavity of this wall make up the humidity levels provide an ideal condition for the growth and multiplication of microbiological entities. In a review of 13 different fungi found in houses [45] found that microbiological life is sustained on surfaces with a relative humidity greater than 75% at  $20^\circ\text{C}$ , with [46] discussing how factors such as temperature, humidity, substrate. This means that there is significant risk of mould growth in the cavity of Retrofit A. The timber roof joist of the property rest on the solid block wall of the property and is therefore exposed to the relative humidity within the air cavity and at the rear of the brick wall. [47] and [48] studying spruce, the same material used in these joists, found that timber exposed to relative humidity greater than 80% between  $+5^\circ\text{C}$  and  $+50^\circ\text{C}$  was at risk of surface mould growth. For brown rot or decay fungi to form the timber must be exposed to relative humidity greater than 95% implying a moisture content of approximately 25–30%. During conditions below this threshold, for example in the changing conditions within a building moisture cycle, the organisms become inactive but quickly become active again when relative humidity rises to 95%. As the monitoring was carried out in Spring, in which an average rainfall of 77.3 mm was recorded (3% above average), and the wettest months in the region occur in Autumn and Winter long term monitoring is recommended. Long term monitoring of the cavity is required to determine if conditions which will

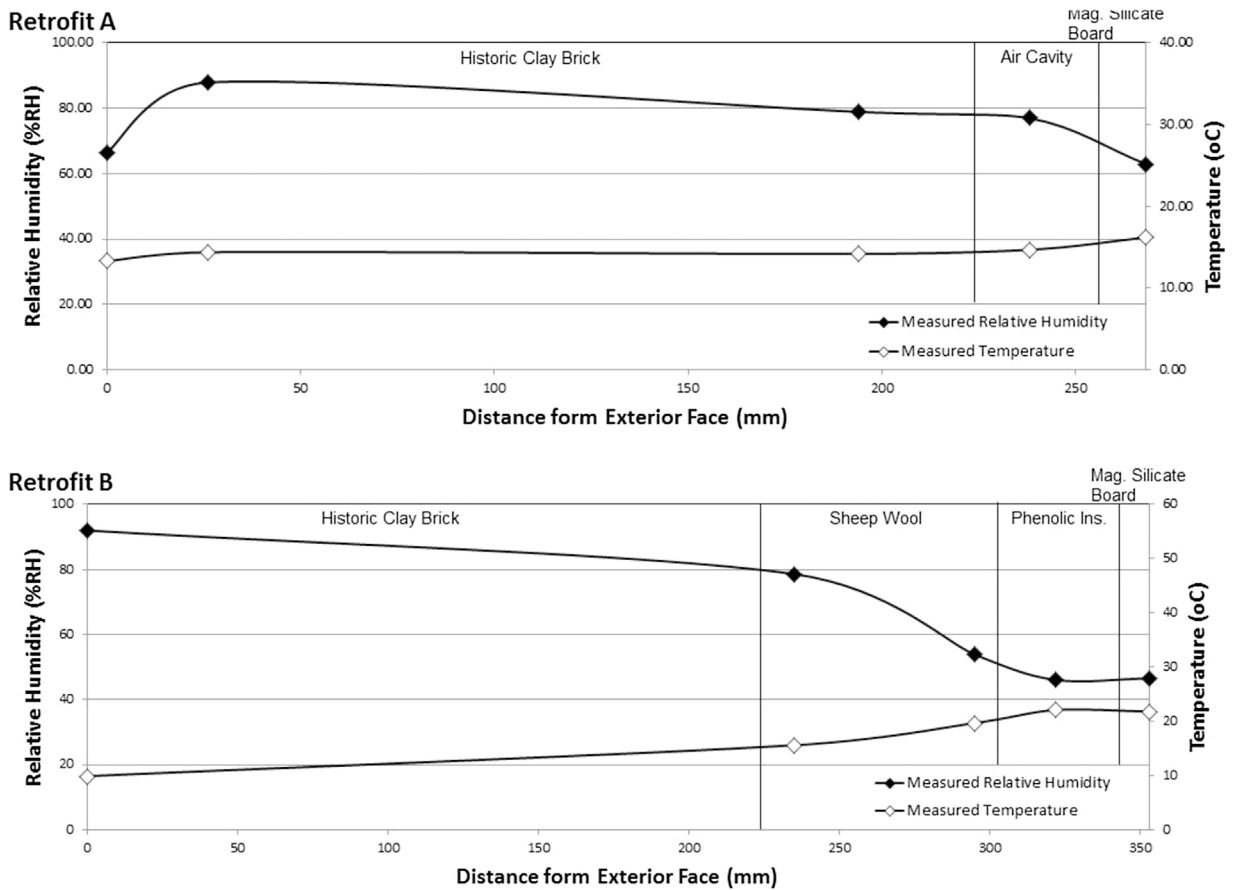


Fig. 9. Wall Temperature and Humidity Profiles of Retrofit A and B.

cause deterioration of the timber will occur and warn if remedial action is needed.

Within Retrofit B it was not possible to drill a sensor location into the solid wall brick due to the presence of the sheep wool insulation impeding the rotary drill bit. The sensor locations through the wall profile for Retrofit B are denoted by triangular markers and numbered 1–5 in Fig. 6b. The sensors are positioned so that the following locations are measured:

1. external environment
2. within the sheep wool 10 mm from the brick wall (235 mm from exterior face)
3. within the sheep wool 10 mm from the phenolic insulation (290 mm from exterior face)
4. Centre of the phenolic insulation (315 mm from exterior face)
5. internal environment.

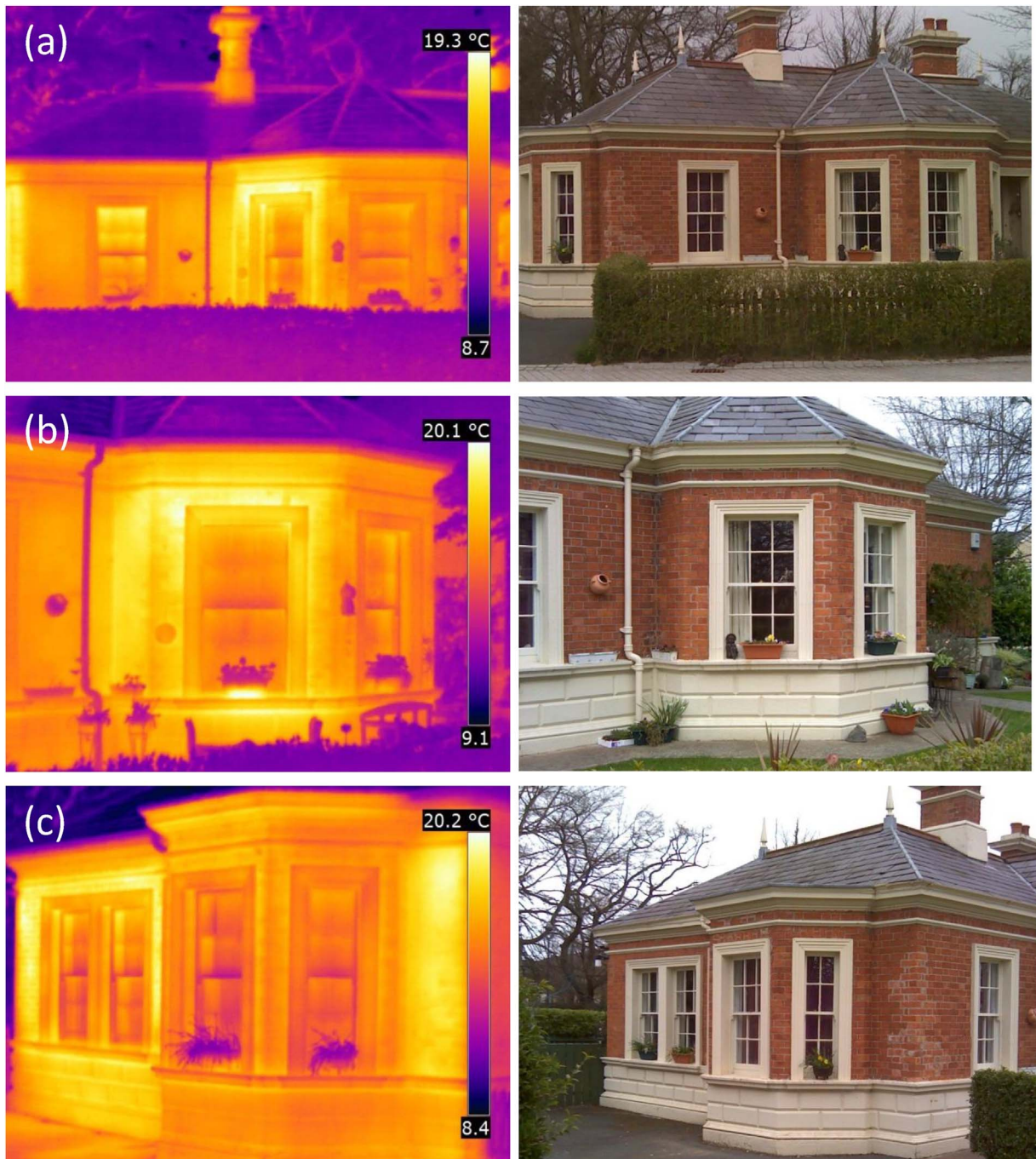
The average conditions found over the monitoring period are plotted in Fig. 9. The sensor located within the sheep wool at the solid wall boundary averaged 78.6% relative humidity (Std. Dev. 0.8%) and this dropped to an average of 53.9% (Std. Dev. 1.7%) at the phenolic insulation boundary. Within the phenolic insulation the relative humidity dropped again to an average of 46.1% (Std. Dev. 0.8%). The sheep wool insulation is buffering the humidity from the internal face of the porous red brick wall leading to a significant drop in relative humidity across it. The relative humidity at the outer wool boundary is in the range that can sustain mould growth, as with the cavity in Retrofit A. Although this type of insulation is hygroscopic in nature and can allow absorption and desorption of moisture while also maintaining a steady thermal conductivity coefficient with a moisture content up to 20%, this level of moisture may cause damage to the timber joists bearing on the external wall [49]. Again long term monitoring of this location is needed to assess the long term build-up and seasonal changes of moisture within the insulation and the floor/roof joists which rest in the solid wall.

### 5.3. Infrared thermography analysis

#### 5.3.1. Thermal imaging and thermal bridge analysis of retrofit a

Thermal imaging of Retrofit A showed no sign of thermal bridging caused by the internal wall junctions to the exterior wall but a





**Fig. 10.** IR and Digital Imaging of Retrofit A (a) Area of increased heat loss above central bay window (b) Specific image of heat loss around bay window detail (c) Increased heat loss in brickwork at both the right of the bay window and far left locations.

number of areas show increase heat loss. Fig. 10 details the main areas of concern found. From imaging of the front elevation of the building (Fig. 10a) it can be seen that there is increased heat loss around the sandstone window mounts and brickwork of the central sash frame. This heat loss can be seen in more detail in Fig. 10b where the areas of highest temperature are concentrated towards the brickwork directly beside the sandstone mount. It is unknown what is causing this increased loss and more destructive investigations would be needed to gain firm conclusions. Possible explanations include reduced insulation in this area or reduced airtightness caused by the differing thermal expansions of each material at the joint. A small area of heat loss is also shown below the sandstone window sill detail, caused by the jointing technique. It is important to note in this case that the white area at the bottom of the glass is caused by the high reflection of the plastic pot, highlighting the importance of scientific judgment when analysing IR and digital images.



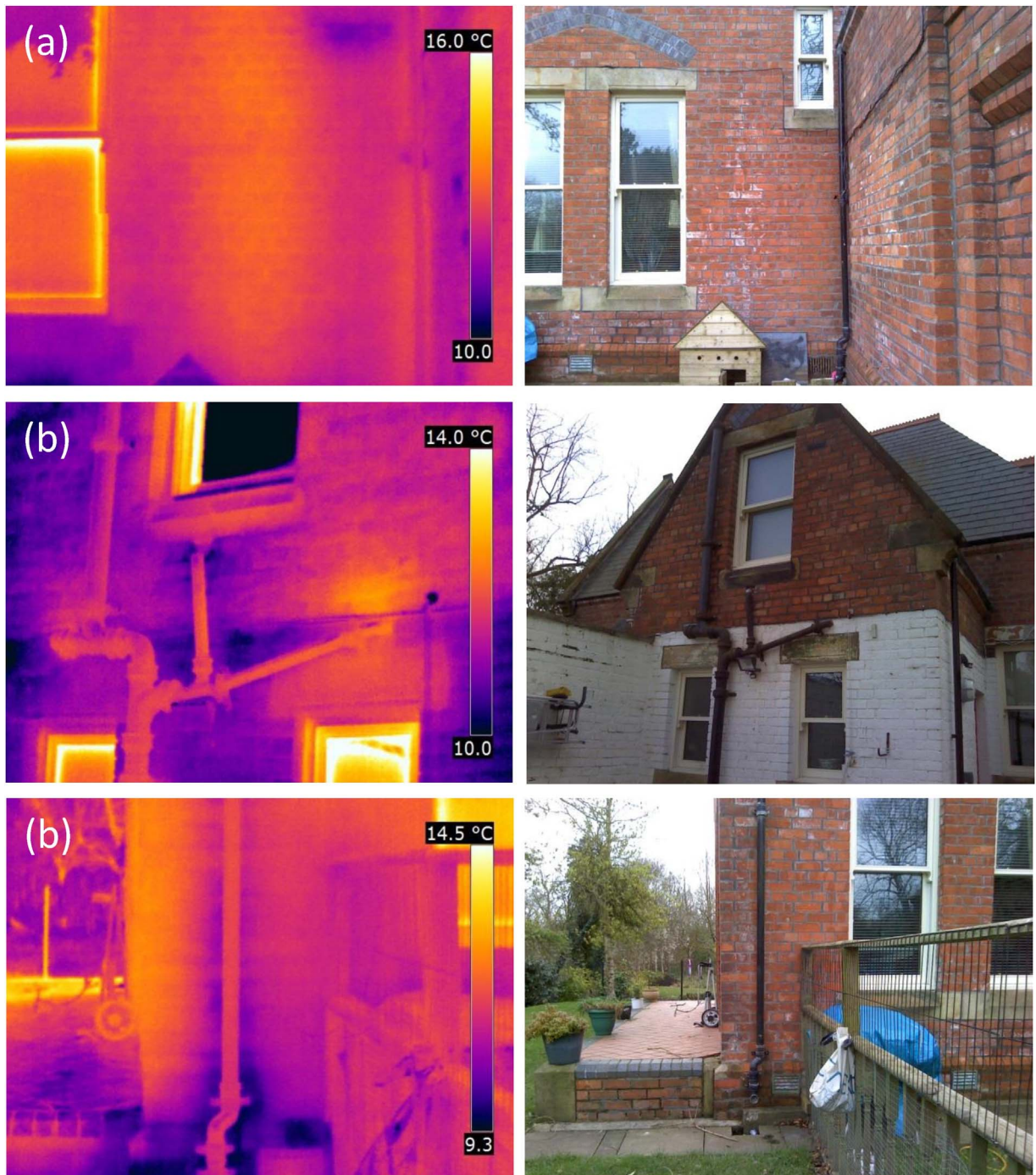


Fig. 11. IR and Digital Imaging of Retrofit B (a) Thermal bridge caused by internal wall junction (b) Missing insulation behind waste pipe exit on right hand side and signs of moisture build up in dark areas (c) Moisture build up at base of down spouting.

Fig. 10c shows areas of increased heat loss in the brickwork in the top right hand side of the image and also the far left location. These areas of increased temperature occur in the central areas of the brickwork and do not obviously protrude to the edges/corners. It can be concluded that these areas in the image indicate areas of reduced insulation level.

### 5.3.2. Thermal imaging of retrofit B

The insulation levels throughout the building were found to be broadly uniform but a number of areas showed signs of thermal bridging as would be anticipated with an internally insulated home. Fig. 11(a) identified an area of thermal bridging caused by an



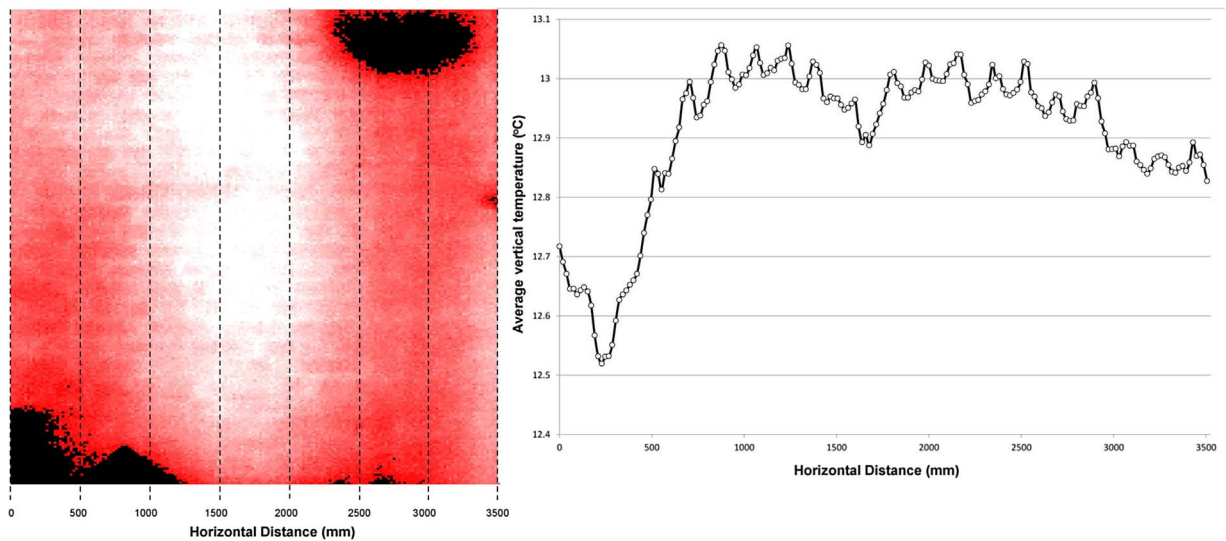


Fig. 12. Post Processed Image and Average Temperature Profile of Wall from Point A to B.

internal wall meeting the external wall meaning no extra insulation can be provided in this area. Anecdotal remedies to this problem include the use of flanking insulation for a distance of approximately 1 m into the room on the adjoining internal wall [50]. This action will increase the path of thermal transmission for heat loss but also increases the area lost within the building due to insulation and may cause unwanted architectural extrusions. The benefit of such a system needs careful analysis at design stage in finite element analysis software which is time consuming and laborious. Using the methodology proposed by [37] the effect of this thermal bridge on the thermal transmittance at this location can be estimated with a confidence level of 95%.

For this analysis it was deemed that moisture on the wall caused by leaking guttering, Fig. 11(a) and the differing materials at the bottom of the image should be excluded from the calculation due to the error they induce. The deleted areas are shown in black colouring in Fig. 12. The incidence factor for the image was then calculated as 1.046. From the results of the *in-situ* thermal transmittance test the wall had a thermal transmittance of  $0.21 \text{ W/m}^2\text{K}$ . When the incidence factor is applied to this image it was found that the actual thermal transmittance increased to  $0.22 \text{ W/m}^2\text{K}$ . The average of the vertical temperature pixels along the horizontal image length of 3500 mm has been plotted in Fig. 12. This graph shows that the average temperature across the thermal bridge changes from  $12.52^\circ\text{C}$  to a peak of  $13.06^\circ\text{C}$ , a relatively small temperature increase but this alone is not sufficient to assess the impact of the thermal bridge without the use of a method similar to the one described. This result shows that although the thermography makes the thermal bridge seem significant due to the stark colour change, and this may be used to justify flanking insulation in the internal wall, the actual increase in heat loss is small. The actual thermal transmittance in the area including the thermal bridge has been shown to be smaller than the design value,  $0.24 \text{ W/m}^2\text{K}$  (Table 1). In this case it has therefore been shown that the effect of thermal losses due to bridging of internal walls does not have a significant effect on the overall fabric performance.

The thermal image in Fig. 11(b) shows a second area of low insulation around the waste water pipe from the main bathroom as well as potential moisture issues around the sink waste pipe situated below the window sill and at the T junction of the sink and toilet waste pipes shown as dark colouring. Other moisture related issues were found at the base of down spouting in Fig. 11(c). These moisture accumulations are of concern due to the high humidity recorded in the wall assembly of Retrofit B.

#### 5.4. Discussion on hygrothermal performance of the building fabric

The *in-situ* thermal transmittance testing of Retrofit A found previously unknown construction detailing errors which meant actual performance was worse than design performance. The detailing error was caused by the cavity behind the plasterboard insulation being directly open to the cold roof space. In contrast, the thermal transmittance of Retrofit B proved to be operating better than designed. The quantitative analysis *via* infrared thermography showed that the effect of thermal bridging from the internal walls of Retrofit B was negligible. But both internal insulation systems showed high humidity within wall fabric make up which could lead to long term durability issues. Long term monitoring is needed to assess the effect of this in more detail and in particular the seasonal hygrothermal cycles of drying and wetting that the wall is likely to go through, The long term durability of the timber floor joists are of particular concern as well as the durability performance of the sheep wool insulation in high humidity environments.

## 6. Conclusions

Through the detailed investigations carried out on two internally insulated solid wall homes, Retrofit A and B, 7 and 8 years respectively after completion of the works, it was found that:

- Specification of MVHR systems based on tracer gas and blower door test results over the two retrofits showed conflicting results. Continuous CO<sub>2</sub> monitoring showed that a MVHR system was not needed in Retrofit A but was needed in Retrofit B.
- A performance based specification via CO<sub>2</sub> logging was proposed for determining the need for a MVHR system, therefore allowing the landlord flexibility in adding a system only when needed. Such a technique would account for changes occupancy levels and behaviour which may mean a system is needed due to the fluctuations in whole building hygrothermal performance.
- In Retrofit A construction detailing errors resulted in the wall thermal transmittance being below design values with high internal humidity being recorded in the cavity.
- Quantitative detection of thermal irregularities showed that the effective thermal transmittance in the walls of Retrofit B was better than designed, even when accounting for thermal bridging losses of interior walls. High humidity was also measured in the insulation layers but no reduction in *in-situ* thermal transmittance was found when comparing values to those determined at completion.

Future work will include long term monitoring of the case study houses to assess the seasonal hygrothermal effects on building performance with a particular focus on material durability.

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